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Power Conditioning in the National Ignition Facility

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Introduction

The National Ignition Facility (NIF) is a 192-beam inertial confinement fusion machine that has been fully operational since May 2009, with more limited operation as far back as 2002. The Power Conditioning System (PCS) supports the NIF mission by driving 7680 flashlamps that pump laser slabs in the main and power amplifiers of the infrared section of the laser.

On a typical target shot PCS stores more than 325 MJ over the period of a minute before delivering the energy to the flashlamps. Peak current exceeds 100 MA and peak power exceeds 1 TW. PCS must operate reliably for hundreds of shots per year.

PCS Architecture Details

Many of the technical details of PCS have been published previously and hence will not be repeated.[1-3] To accomplish its mission PCS relies on 192 modules deployed throughout 4 capacitor bays. Each module comprises a pre-ionization/lamp check (PILC) circuit and a main energy storage module (MESM) along with a control/data acquisition system. The PILC circuit relies on a single high voltage power supply, a pair of high voltage capacitors and a single trigatron switch. The MESM on the other hand is currently configured with 20 high voltage capacitors (expandable to 24), a pair of power supplies and a single spark gap switch. As depicted in **Figure 1**, the PILC and MESM share waveshaping and transmission hardware in the form of ballast inductors and underground residential distribution (URD) cable. Both the PILC and MESM capacitors are nominally charged to 24 kV for laser shots. The PILC circuit has two primary functions: to prepare the lamps for the arrival of the main discharge and to verify that lamps remain intact following the main discharge. The lamp check occurs approximately 5 minutes after the laser shot.

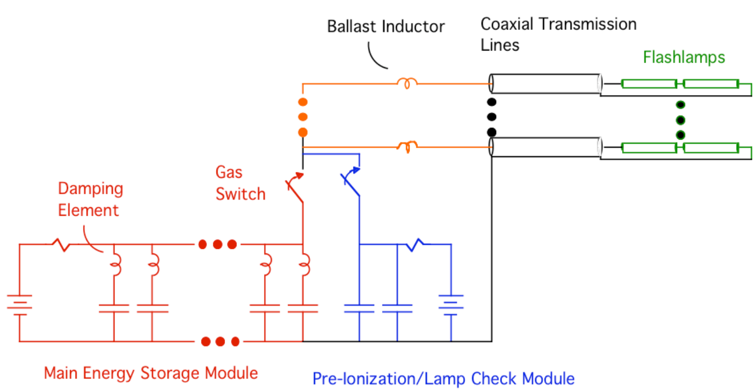

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Figure 1. Simplified Schematic of the NIF Power Conditioning Module.

PCS was designed and deployed with a line replaceable unit (LRU) maintenance philosophy in mind: in particular, most failed components/assemblies replaced in the facility and repaired offline. The majority of module LRUs can be replaced in a half-hour or less. Others, such as power supplies (2 hours) and switches (4 hours) represent both additional effort and additional safety considerations including lock-out/tag-out and module "safing[†]." Note that the modules, while nominally mobile (by means of air bearings) and thereby replaceable, have never been treated as such. All 192 modules remain in their original locations even for major repairs.

Modules are organized into groups of eight (8), supporting 8 NIF beams, the fundamental unit of NIF referred to as a bundle. Six bundles represent a capacitor bay. Two capacitor bays support a laser bay and two laser bays represent all 192 beams of NIF.

NIF has eleven slabs in the main amplifier and five slabs in the power amplifier (with expansion to seven slabs as an option). The corresponding module configuration is shown in **Figure 2**. Module 6 is the lone module in a bundle that drives flashlamps in both the main and power amplifiers. Note that all cables and ballast inductors associated with a given module have uniform properties.

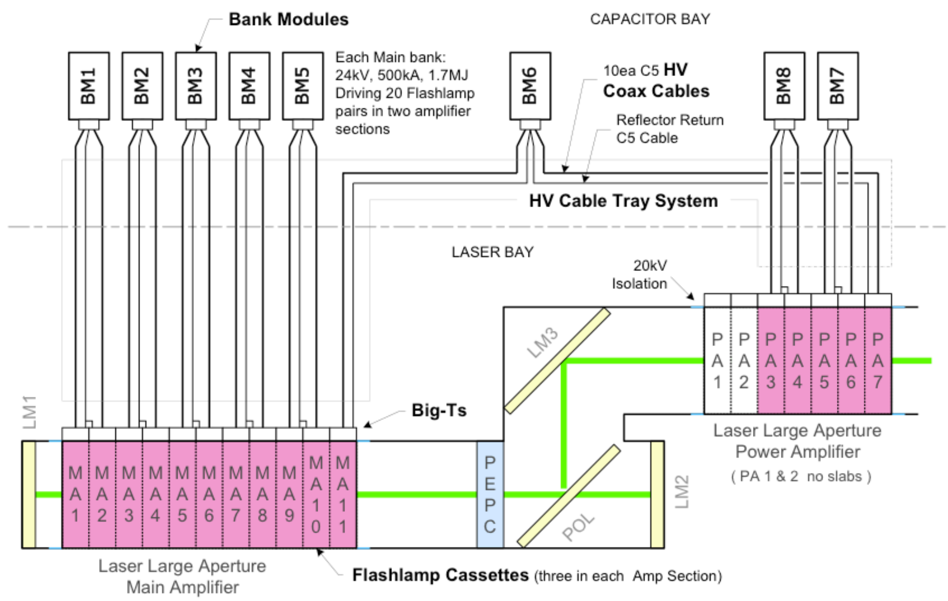

Figure 2. Correspondence between bank modules and laser slabs. Currently, eleven slabs are installed in the four-pass main amplifier and five (of a possible 7) slabs are installed in the double-pass power amplifier. The figure also depicts the relative locations of the Plasma Electrode Pockels Cell, a polarizer and the laser mirrors.

PCS Operational Details

[†] Safing refers to the process of rendering the module safe (following LOTO) by verifying (in order) that the dump relays are down and dump resistors are intact, capacitors are fully discharged and all the capacitor and cable capacitance is present. Ground sticks are then inserted and ground sets put in place to ensure that the banks cannot charge. Only following this process can a module be accessed. Note that permissives from the Safety Interlock System are removed and module status verified remotely (capacitors discharged, nominal waveforms acquired and dump relays closed) before the Capacitor Bays can be unlocked and entered. LOTO and safing for a single module can be completed by a two-person crew in approximately 15 minutes.

The charging sequence for a module is illustrated in **Figure 3**. The PILC circuit begins its charge cycle first with the pair of MESM supplies turning on within a few seconds of the initiation of the PILC charge. Both the PILC and MESM charge and then hold, with the power supplies regulating the voltage to 1% and 0.05%, respectively. For so-called warm shots (in which the target is not cooled to cryogenic temperatures) the hold is only a few seconds, varying slightly from bundle-to-bundle due to purposely staggered starts. Maximum system draw from the AC power grid is approximately 10 MW. For "cryo-shots" the hold is much longer, approaching 30 seconds. The extended hold-time allows the target shrouds to be opened and the target to be "quenched" without the issue of a module failing to charge. (The extended hold is not without consequence. A small number of switch prefires have been experienced during this 30-second wait time and the stress on the capacitors is increased.) Three subdivisions of the charge-and-hold sequence are designated and recognized by the system control software: Region A: the time from charge initiation until the PILC is fully charged; Region B: the period between the end of PILC charging till the end of main bank charging; Region C: the period from main bank end of charge until the laser fires. Software aborts for pre-fires in regions A and B so the target can be preserved. "Wrapping around" for a second attempt typically takes about 30 minutes.) In region C a PILC pre-fire is ignored with minimal effect on laser performance but a slightly increased stress on the flashlamps. (The severity of a MESM pre-fire or no-fire is much greater. The loss of the pump energy for a pair of slabs results in a 70% loss of that bundle's laser output as the unpumped slab becomes an absorber.)

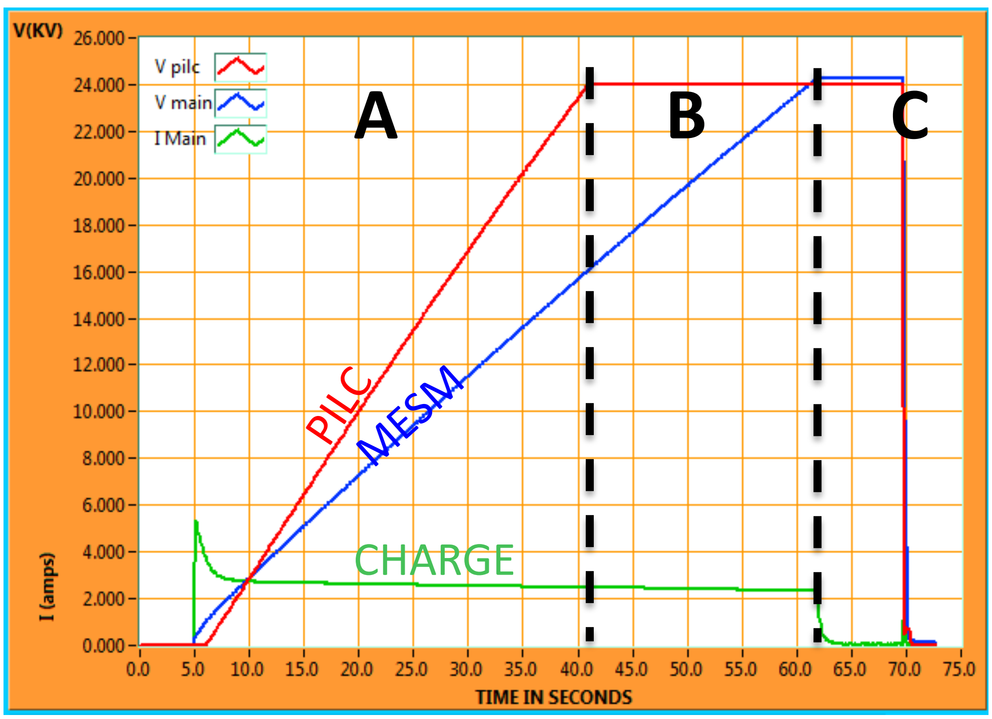

Figure 3. Charge sequence for a single module. Depicted are the PILC voltage, the voltage and charging current of the main energy storage module. Regions A, B and C are defined for use by the control system and its response to a fault. Region C can vary between a few seconds (as for a non-cryogenic shot) to as much as 30 seconds for a cryogenic shot.

Triggers for the PILC and MESM circuits are supplied by the facility's Integrated Timing System (ITS). Timing for all modules in a bundle is identical with the triggers signals passing through optical splitters before arriving at the individual modules.

A gas chassis in each module sets and maintains the pressure in the spark gap switches. Due to a recent upgrade in the operating system the valves of the gas chassis remain open until the main capacitor bank reaches 12 kV. (This reduces the effects of leaky switches but still allows the internal hardware of the chassis to be protected from the pressure pulse from the switch and provides sufficient time for any transient (gas) conditions in the switch to damp out before the electrical stress reaches its maximum value.) In addition, the gas chassis is used to purge gas byproducts and particulate from the switches following each shot. It has been observed that it important to begin the purge sequence immediately after the shot, while the particulate is still "in solution" to maximize the amount that is extracted.

A single operator is responsible for all 192 modules during a shot cycle. Interaction with the computer control system is via multiple GUI interfaces. Operators can quickly "drill down" to the offending module and assembly if and when issues occur, guided by color-coded icons and three categories of error messages, depending on severity.

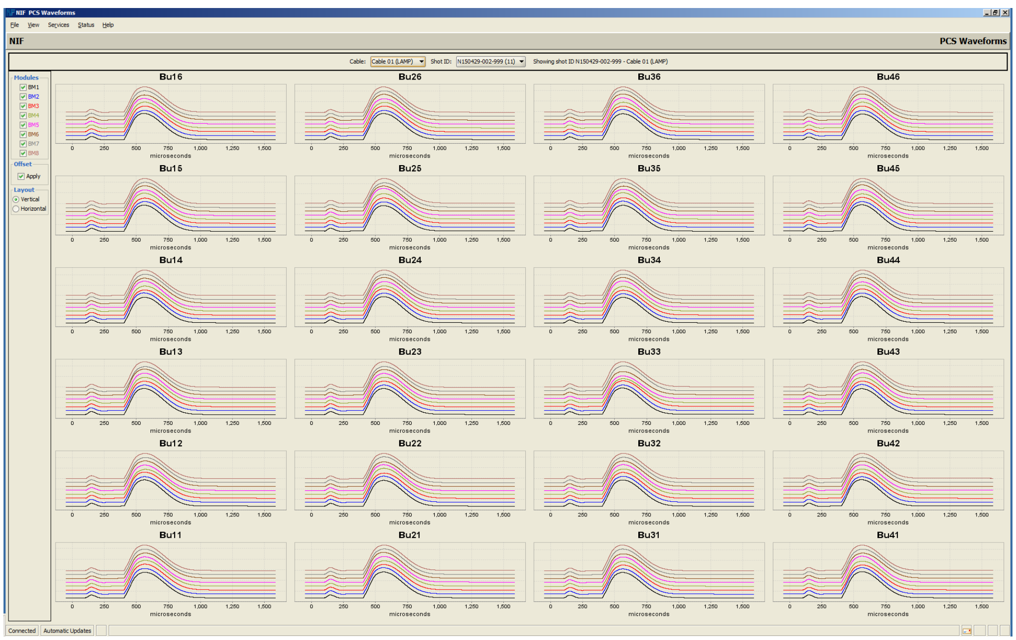

Figure 4. GUI display of output currents of all 192 modules for one shot enables operator to quickly determine the source of subtle issues and quickly "drill down" to more detailed information.

<u>Operator/Maintenance Worker Training and Qualifications</u>

Currently a team of 9 operators (recently up from seven), split between 4 overlapping thirteen-hour shifts, operates PCS 24 hours per day, five and half days per week. Unique for NIF, there is no separate maintenance crew for PCS. In addition, the same group of operators is also responsible for operation and much of the maintenance of the Plasma Electrode Pockels Cell (PEPC) system. The operators handle the vast majority of PCS maintenance on the single day per week that is dedicated to system upgrades, software deployments and system maintenance. They also handle much of the testing that goes along with component and assembly development in an offline facility. The technician team is currently augmented by one full time engineer/system manager and another engineer that splits time between three separate pulsed power systems.

The majority of the operators have prior military training (in electronics or equivalent) or a bachelor's degree in a technical field (technology, engineering, physics) or both. The goal has been to hire operators who are overqualified for routine system operation but who have the ability to both troubleshoot, replace and/or repair hardware that requires either routine or emergency attention. Because of the round-the-clock nature of NIF operation, the goal has been to give the operators maximum autonomy in dealing with off-normal conditions, with the understanding that the engineer(s) provide appropriate insight and backup. Operators typically are proficient in operating the GUI-based control system within three months of arriving but take as much as two years to become proficient in all aspects of troubleshooting and repair.

Operator training is rigorous and is documented by qualification cards and written tests. Workers are formally exposed not only to the specifics of the system at hand but the broader concepts associated with pulse power systems including, but not limited to: basic pulse power circuits, transmission lines, transients on transmission lines, field enhancement, basic magnetics, pulse transformers, three-phase power, action, RMS values, gas and solid state switches.

Worker safety is paramount. Incoming operators must complete approximately 60 safety training classes, split between institutional, programmatic and system-specific courses. Periodic retraining/requalification is also required for subjects such as lock out/tag out, high voltage safety, electrical safety, and CPR. All work is preceded by a pre-job brief (which covers task details, division of labor, potential hazards and hazard mitigation) and is authorized by a work permit.

The vast majority of tasks within PCS are covered by a written procedure or checklist. Recently, a number of procedures and checklists have been migrated to electronic tablets, greatly reducing the time spent printing documents and reducing the effort associated with archiving information. The goal is to have all safety/maintenance documents in electronic format as resources become available.

Operators are responsible for writing problem logs to document any and all issues with the system. Included in the problem log is a description of the problem, its time of occurrence, affected module(s) and problem resolution. Problems are reviewed each day to guide daily tasks. They are also re-reviewed, primarily for trends, in a program RAM meeting that occurs three times per year.

Maintenance Philosophy

The maintenance philosophy for PCS has evolved over the years as the facility has changed the way it operates. Initially, the majority of maintenance was completed on day shift as the majority of shots were taken at night. Later, maintenance was opportunistic as there were no designated periods for maintenance, with shots occurring on any day, any shift. Shots are now scheduled on both shifts, from Saturday evening through Friday morning. Two of the three maintenance shifts are designated for PCS reactive and preventive maintenance as well as system upgrades and retesting. (The third shift is dedicated to maintenance for PEPC.) Note that requirements for module (re)testing are very restrictive. Capacitor bays and laser bays must be swept (verified to be completely vacated); the laser must be aligned with downstream beam blocks in place before the modules can be energized. This places a premium on getting the job done right the first time. Thus, the majority of tasks are completed with the use of the aforementioned detailed procedures / checklists or both with workers providing secondary verification of all steps.

In addition to weekly scheduled maintenance the team takes advantage of multi-day quarterly Facility Maintenance and Refurbishment periods (FM&R's), which allow more extensive work to take place. The vast majority of periodic tasks are scheduled through the commercial application SMaRT, providing task reminders and giving a window for completing the task. Examples of routine maintenance items: gas chassis calibration, power supply calibration, testing of the dump resistors, internal module inspection, cable/flashlamp interfaces and grounding system inspections.

Operational Experience and Recent Performance

NIF has fired nearly 2000 target shots since the facility became operational in May 2009. Many of the early "teething" issues with power conditioning have been corrected. Other issues have come to light as the number of shots has increased. Addressing these issues has become even more critical as the program has increased the nominal shot rate to 300 shots per year. (This number represents only target shots.)

During the past 18 months, the PCS system responsible for a pair of aborts out of well over 400 system shots. These were due to a PILC switch pre-fire at T minus 6 seconds before the shot, making it impossible for the target to recover, and a capacitor failure that forced the corresponding module to be taken offline for approximately a week while it was refurbished. This gives a reliability of 99.5% (by the NIF definition) for the PCS system. In addition, there have been a total of 42 shot delays of various origins averaging 0.9 hours each. The typical response to a PCS problem a "software wraparound" to begin the final countdown over, with the wraparound also contributing to the delay.

Major operational issues

Power supplies

Initially, power supply problems represented a large fraction of the problem encountered. Manufacturers of both the PILC and main supplies have been able to identify and address the problems to a level such that power supply problems are rare. All PILC supplies are going through an upgrade process at the vendor that is expected to complete in 2017.

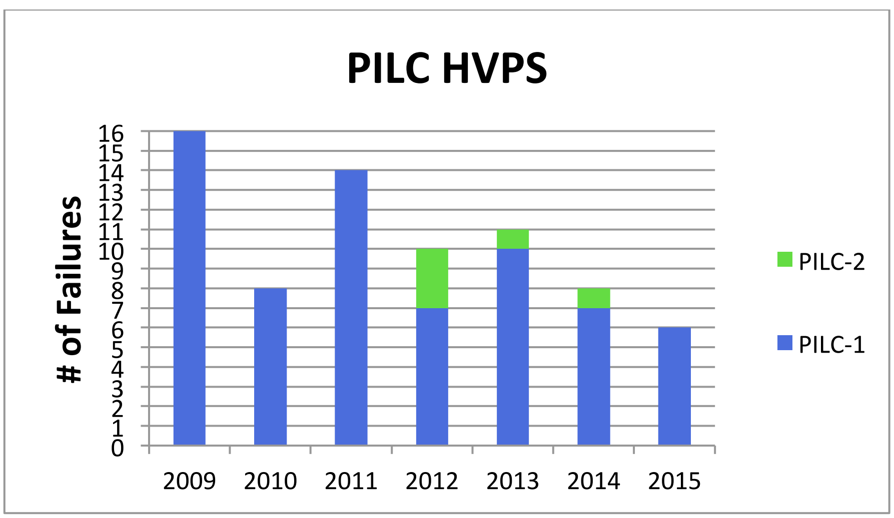

Figure 5. PILC power supply failures. Upgrades to the supplies began in 2012 (PILC-2) and will continue for another 2 years. Failures for 2015 are projected. Failures of main supplies run substantially lower (less than 10 in the last four years) despite the fact that there are twice as many in the facility.

Switches

The PCS software calculates the pressure operating point for each switch on each shot, based on the initial gap, the accumulated charge transfer associated with that switch and the applied voltage for the shot at hand. A breakdown curve initially based on the erosion characteristics of a single switch of each type has been revised as more operational data has been accumulated over the past years.

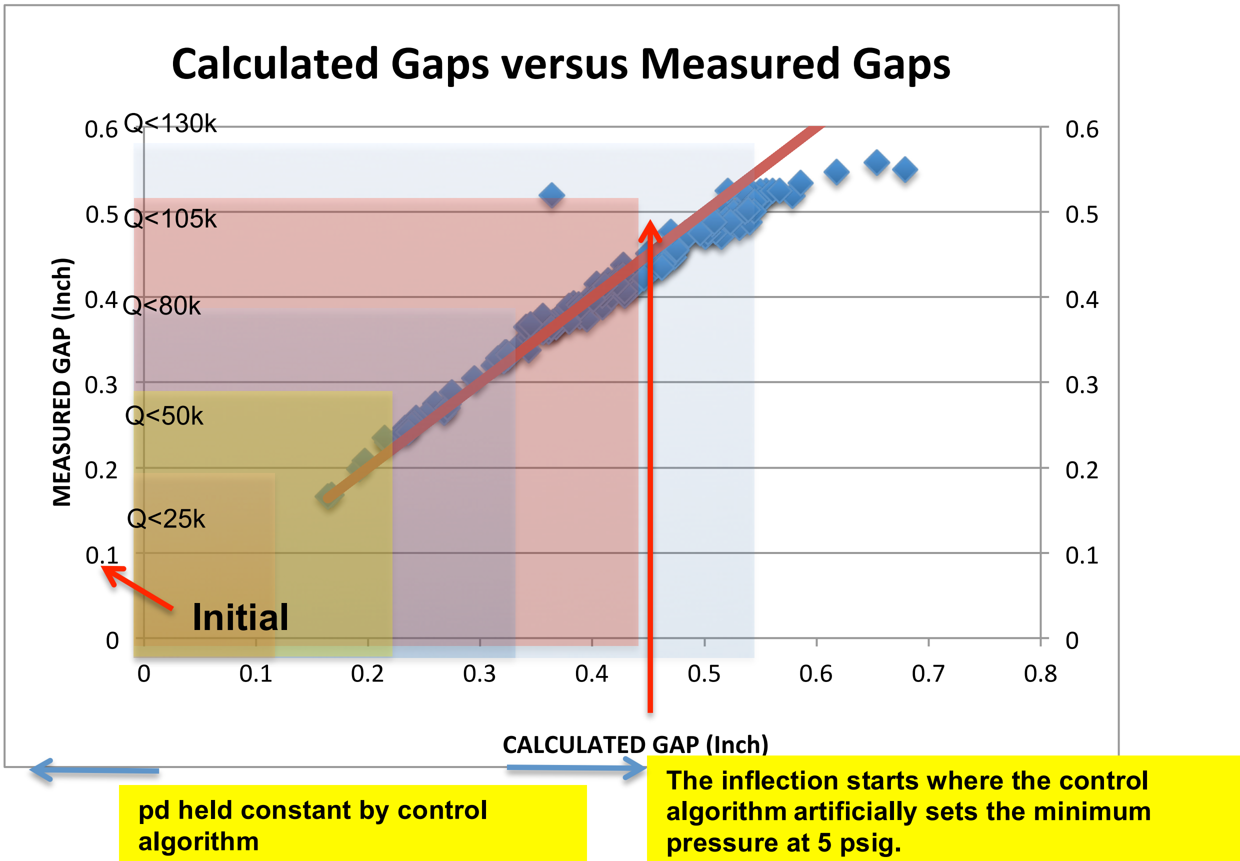

Figure 5. Software sets the switch pressure based on charge voltage and gap size, which is inferred from charge transfer and the original size of the gap. The linear fit applied over the majority of electrode life has been adjusted over the years to more accurately reflect actual erosion data. Pressure is held artificially high for the first 100 shots and is artificially set at 5 psig toward the end of electrode life.

Main and PILC switches nominally operate at 50% and 65% of their self-breakdown potentials, respectively. (Originally, the PILC switches operated at 70% of SB but were "dialed back" in 2012 to reduce the number of pre-fires.) A number of the pre-fires have been traced back to issues with the insulation around the trigger electrode. Aluminum oxide (ε_r ~9) finds its way to the horizontal surface of the lower main electrode and acts as a field intensification point, leading to a breakdown.

The main switch is triggered with a 110 kV pulse, stressing the main gap to approximately 2.7 times its self-breakdown value. No-fires are rare but have occurred even with nominal trigger pulses applied. In 2010 it was determined that the switch gap was eroding slower than the initially predicted, causing the pressure setting for the switch operation to be set low thus raising the probability for pre-fires. A new algorithm was calculated based on gap measurements of large numbers of switches and deployed in the facility.

Whereas a reasonably linear pressure-charge transfer curve is employed in the software for the majority of switch life a significant deviation is employed in the early stages of operation. Essentially, the pressure is held artificially high for the first hundred shots to prevent prefires.

In the PILC switches no-fires were especially prevalent following the reduction of the percentage self-breakdown from 70% to 65% following a series of two pre-fires during high profile shots. Numerous switches were replaced or refurbished to mitigate the problem. Under normal circumstances the no-fires result from one of 3 issues: trigger generator problems (SCR or diode failures), trigger cable failure or insulation failure around the trigger electrode in the trigatron (which results in plasma formation well below the surface of the main electrode).

Originally, main switch life (as defined by the life of a set of electrodes) was projected to be 240-300 kC, based on limited initial testing. However, extensive operational experience has shown that as the gap expands the incidence of pre-fires, no-fires and incidence of leaks increases. (Given the number of switches and the unacceptable nature of any of the problems from an operations standpoint large gap operation is not tenable.) Of these, the most burdensome (in terms of labor) is the increase in the number of leaks. (See Figure 6.) There are a number of contributing factors. Probably the most important is the orientation of the switch. The ideal orientation would place the insulator toward the top of the switch and the sealed metal housing at the bottom. Unfortunately, the module configuration forces the insulator to be oriented toward the bottom so that any debris from the switch housing, electrodes (which fails to combust completely) or the insulator falls into the region near the o-ring seal. Eventually, the debris, which can then be injected into the o-ring/groove region by the pressure pulse associated with the discharge, leads to a seal failure.

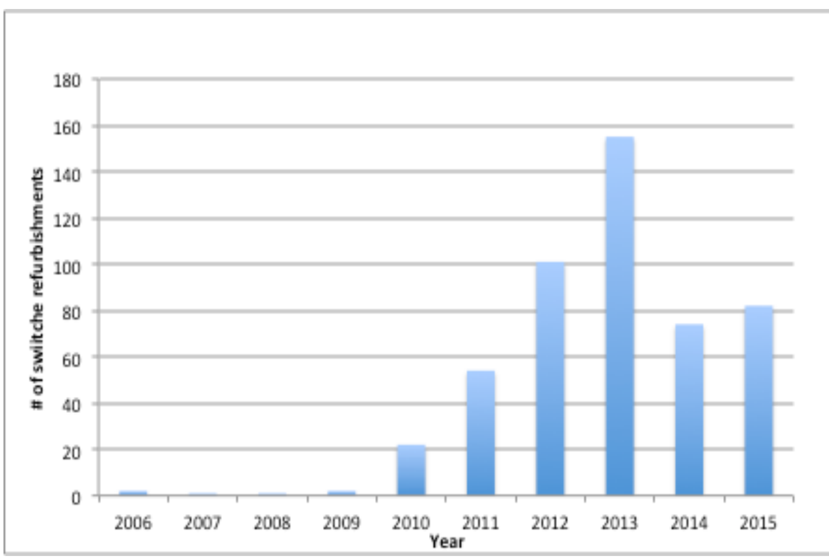

Figure 6. Main switch refurbishments reflecting accumulated charge transfer. Refurbishments generally result from leaks or end-of-electrode-life.

As such, switches are typically re-electroded at or about 120 kC, allowing the clock to be effectively reset. (Refurbishment above 120 kC “last” only ~30 kC before being required again to address leak issues.) A single intermediate refurbishment between 0 and 120 kC is projected as a norm. The insulator and o-rings are replaced before the switch is returned to service. A pair of experienced operators can complete this maintenance is 4 to 6 hours so the activity is scheduled for maintenance days. Leak checks on all switches are performed several times per week so that “leakers” can be identified and targeted for maintenance.

Recently, system software has been changed to allow the gas chassis valves to remain open until the capacitors reach half voltage. This mitigates to some level the effects of leaking switches, the primary problem, of course, being prefires due to reduced pressure in the switch.

Capacitor failures

Four capacitor failures have occurred with all attributed to infant mortality issues associated with insulator punch-through and runaway self-healing. Damaged/destroyed capacitors were replaced and the modules were returned to service in approximately 1 week in each case. To offset the loss of a module within the bundle the pre-amplifier was temporarily run “hotter.”

Miscellaneous failures / issues

The original designs were determined to be faulty for both the PILC switch connection to its bus and output cable. Connections were upgraded universally to much more robust designs. No failures have been experienced since the upgrades were implemented over a six-month period.

There have been no failures of the main switch trigger generator. The trigger generator for the PILC switch has experienced a small number of failures, primarily trigger SCRs and diodes upstream of the pulse transformer.

The valves of the gas chassis are closed before the shot to protect it from the pressure pulse that ensues when the switches fire. Despite this precaution, large numbers of transducers failed, apparently reaching the end of their operational life rather than being overstressed. Since all transducers were replaced only 2 have failed.

Solid state relays in the gas chassis switch AC power to the trigger generators, etc. A number of these solid-state devices have failed and been replaced.

A small number issues have been encountered that were attributable to workmanship problems. An example is an 85 mΩ resistor that acts as the interface between the PILC and MESM circuits. The resistor had not been secured properly during the installation cycle and resulted in a failure at the interface. The failure remained undiscovered until the PILC pulse could no longer bridge the gap at the interface.

The embedded controller and data acquisition system reside in an EMI rack. Despite the magnitude of the noise generated when the switches fire these systems with their 1980’s technology have been very robust. The main problems have been with media converters, especially when the system reboots and the embedded controllers communicate with front-end processors to download their code. Weekly scans of the number of I/O errors for the media converters allows units to be replaced before the problems cause major issues.

Software

A separate team of software developers design, implement and maintain the code associated with PCS. There are essentially three levels of interacting code: the embedded controller software, the front-end processor code and the so-called shot layer. The embedded controller controls a single module. The front-end processor controls a single bundle (8 modules) and the shot layer controls all 192 modules (along with all other NIF systems).

An instance of each new release is tested in an offline facility using actual hardware to debug and functionally test the code. This has proved to be invaluable as code of ever-increasing functionality and complexity is readied for the facility.

Sparing

Spares are maintained for essentially all components and assemblies short of the module enclosure. A module can be completely rebuilt from new hardware in less than a week. Most hardware is distributed in all four capacitor bays to minimize delays. Larger assemblies are kept in a single bay.

Spares lists, based on a master parts list, are reviewed and re-ordered on a regular basis.

Conclusions

The Power Conditioning System for NIF continues to operate in a manner consistent with the RAM requirements of the facility. The operational keys are:

- Operator/maintenance worker quality and training
- Scheduled preventive and reactive maintenance
- Well-developed processes (including procedures and checklists),
- Adherence to maintenance schedules, appropriate levels of spares,
- LRU-based maintenance
- Improvements in design and implementation, driven by problem log documentation and analysis
- Improved response and better preparation to off-normal events through lessons learned
- Improved diagnostics and data acquisition
- Software upgrades eliminating unnecessary aborts
- Maintaining and strategically staging ready spares

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